Experimental Puzzles in Heavy Flavor Decays
Anomalously high η' appearance in charmless strange B decays - Flavor SU(3) breaking in Charm Decays

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Abstract

Simple experimental tests are proposed which can clarify the origin for the anomalously high η' appearance in charmless strange final states in B decays and can investigate the the nature of SU(3) symmetry-breaking in weak heavy flavor decays..

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Most theoretical predictions in heavy flavor physics begin with well defined models and assumptions. When the predictions disagree with experiment, possibly indicating the existence of interesting overlooked physics, it is not clear which of the assumptions underlying the predictions have gone wrong or whether there may be clues to evidence for new physics beyond the standard model. This is particularly relevant to CP violation where the evidence supporting the Kobayashi-Maskawa phase as the explanation is essentially one piece of data fit by one free parameter and any unexpected experimental signals should be thoroughly explored.

We develop an alternative approach to examine two puzzling phenomena where experimental results challenge conventional wisdom: (1) the anomalously high η' appearance in charmless strange final state in B decays ; (2) Some apparent violation of SU(3) predictions relating Cabibbo-favored and doubly-forbidden transitions in charm decays. We look for experimental tests which can bring new insight into apparent contradictions and hopefully bring evidence for new physics that may be hidden in the puzzles.

I. THE $B \to K\eta$ - $B \to K\eta'$ PROBLEM

The large experimental branching ratio [1] $BR(B^+ \to K^+\eta') = 6.5 \pm 1.7 \times 10^{-5}$ as compared with $BR(B^+ \to K^+\eta) < 1.4 \times 10^{-5}$ and $BR(B^+ \to K^o\pi^+) = 2.3 \pm 1.1 \times 10^{-5}$ still has no completely satisfactory explanation and has aroused considerable controversy [2].

A. A parity selection rule can separate two types of models

We note here a clear experimental method to distinguish between two mechanisms proposed to explain this high η' appearance and the high η'/η ratio in charmless strange B decays.

1. Treatments where the enhancement arises from an additional diagram; e.g. the anomaly, gluon couplings to the flavor singlet component of the η' or intrinsic charm [3,4]. This diagram is often called an "OZI-forbidden hairpin diagram" and is described by fig. 1 using the flavor-topology description [5]. The enhancement is universal and should appear in all similar final states. In particular, it should be independent of the *parity* of the final state.

2. Treatments where the enhancement arises from constructive interference between diagrams producing the η' via the strange and nonstrange components of the η' wave function [5]. The sign of the interference should be constructive only for even parity final states and destructive for odd parity final states; and vice versa for the corresponding interference in the η wave function. One example is the model where the gluonic penguin diagram produces the η and η' in charmless strange final states both via the $u\bar{u}$ (fig.2) (or $d\bar{d}$) and $s\bar{s}$ (fig.3) components of these mesons, denoted respectively as η_u and η_s. The two components

interfere constructively for the η' and destructively for the η in all final states of even parity and vice versa for states of odd parity.

This model predicts a parity selection rule in which the η/η' ratio should be large in charmless strange final states of ODD parity and small in states of EVEN parity. This selection rule should be violated in models of type 1 above which introduce some other parity-independent mechanism for explaining the large η' enhancement found in the $B \to K\eta'$ decay [3,4]

That these considerations lead to a large η'/η ratio for the $K\eta$ and $K\eta'$ final states and the reverse for the $K^*(892)\ \eta$ and $K^*\ \eta'$ has been pointed out [2]. This seems to agree with experiment, although so far the $K^*\ \eta$ has been seen and the $K^*\ \eta'$ has not.

Note that the simple tree diagrams (figs. 4 and 5) can produce the η and η' only via their nonstrange components. These contributions are eexpected to be relatively small and in any case cannot contribute to a large η'/η ratio since these diagrams contribute roughly equally to both final states.

B. Experimental consequences of the Parity Selection Rules

We now note some further experimental consequences of this parity rule which can be checked possibly with already available data.

1. The $K\pi\eta$ and $K\pi\eta'$ states all have odd parity, even when the $K\pi$ is not in a K^*. Therefore the selection rule predicts that the $K\pi\eta$ should be much stronger than $K\pi\eta'$ when summed over all final states. Using the better statistics obtainable by summing over all charged and neutral B decays. one may get a clear test between the two models. A strong enhancement of the η over the η' would provide strong evidence against models that produce the η' via the SU(3) singlet component; e,g, gluons, anomaly or intrinsic charm.

2. An appreciable inclusive signal for $B \to K\eta' X$ has been reported. A measurement of the spectrum of the "missing mass" M_X can check the validity of the parity selection rule, which requires M_X to be at least two pion masses. Confirmation of this selection rule would also simplfy the partial wave data analysis by ruling out large contributions from resonances with large $K\pi$ decay modes without needing any complicated fits to mass plots; e.g. the scalar $K_o(1430) - (93\% - K\pi)$, the tensor $K_2(1430) - (50\% - K\pi)$ and higher respnances like $K^*(1680) - (39\% - K\pi)$.

3. The measurement of the TRANSVERSITY in the final states $\eta\rho K$, $\eta'\rho K$, $\eta\pi K^*(892)$ and $\eta'\pi K^*(892)$ gives an unambiguous signal for the PARITY of the final state (whether it is 0^+ or 0^-) independent of the quantum numbers of the $K\pi\pi$ state recoiling against the η or η'. This is the measurement of the polarization of the vector meson in its rest frame with respect to an axis normal to the VPP plane [6]

4. An η or η' recoiling against a K^* resonance with NATURAL parity (even P for even J and odd P for odd J) has odd parity and should give a final state favoring the η over the η' . The opposite is true for a recoil against a state with UNNATURAL parity. the K and $K^*(892)$ states are special cases of this prediction.

5. One should look for $K\eta$ and $K\eta'$ resonances in the states $K\eta X$ and $K\eta' X$. Here the even parity resonances should favor the η' and the odd parity resonances favor the η.

C. Possible new physics and CP violation

If the parity selection rule is violated, there is always a possibility that it is due to new physics that can produce CP violation. One simple test of any far-out idea for direct CP-violation is to compare corresponding B^+ and B^- decays and look for a difference. Since a number of decays to final states containing the η' seem to be enhanced considerably beyond what is expected from conventional models, it would seem reasonable and cheap to check for direct CP violation in such cases. Other cases of anomalously large decays to η' final states which might merit special investigation include $D_s \to \pi\eta'$ and $D_s \to \rho\eta'$.

II. EXPERIMENTAL PUZZLES IN DOUBLY-CABIBBO SUPPRESSED CHARM DECAYS

Cabibbo-favored and doubly-cabibbo suppressed charm decays have been noted to go into one another [7,8] under an SU(3) transformation which interchanges d and s flavors everywhere, This transformation is a subgroup of SU(3) sometimes called a Weyl reflection or a U-spin reflection.

$$d \leftrightarrow s; \quad K^+ \leftrightarrow \pi^+; \quad K^- \leftrightarrow \pi^-; \quad D^+ \leftrightarrow D_s \tag{2.1}$$

Two aspects of this relation which suggest interesting implications of any symmetry breaking are relevant here.

(1) Experimental tests of the magnitude of SU(3) breaking will be relevant in the interpretation of information about the CKM matrix and the unitarity triangle obtained from. standard model analyses of weak decays which assume SU(3) symmetry.

(2) In the standard model the Cabibbo-favored and doubly-suppressed charm decays are proportional to the same combinations of CKM matrix elements and no direct CP violation can be observed. Thus any evidence for new physics that can introduce a CP-violating phase between these to amplitudes deserves serious consideration [7].

A. Relations between Cabibbo-Favored and Doubly-Cabibbo Suppressed D^o decays

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Wolfenstein [8] has noted that the $D^o(c\bar{u})$ which contains no d nor s quarks is invariant under this $d-s$-interchange SU(3) transformation (2.1) and that under this transformation the $K^+\pi^-$ and $K^-\pi^+$ decay modes go into one another as seen in figs. 6 and 7. Thus SU(3) predicts that the doubly-Cabibbo-suppressed and Cabibbo-favored decays to these final states should have the same strong phases.

A recent analysis of the two-pseudoscalar decay modes of the neutral D mesons [9] suggests that the phases are not the same. But the $K^+\pi^-$ and $K^-\pi^+$ final states are charge conjugates of one another. Thus a strong phase difference cannot be introduced by any $K-\pi$ final state rescattering mechanism that conserves charge conjugation; e.g. Regge exchange models [10–14], even if SU(3) is broken. SU(3) can be broken in strong interactions without breaking charge conjugation only in the hadronization transition from the quark level to the hadron level.

$$D^o(c\bar{u}) \rightarrow (su\bar{d})\bar{u} \rightarrow (s\bar{u} \rightarrow K^{*-})_S \cdot (u\bar{d} \rightarrow M^+)_W \rightarrow K^{*-}M^+ \rightarrow K^-\pi^+ \tag{2.2}$$

$$D^o(c\bar{u}) \rightarrow (du\bar{s})\bar{u} \rightarrow (d\bar{u} \rightarrow M^-)_S \cdot (u\bar{s} \rightarrow K^{*+})_W \rightarrow M^-K^{*+} \rightarrow \pi^-K^+ \tag{2.3}$$

where $K^{*\pm}$ can denote a kaon or any K^* resonance and $M^\pm$ can denote a pion or any charged meson resonance, and the subscripts S nd W denote strong and weak form factors. The quark-antiquark pair created from the the weak vertex is expected to hadronize with a weak pointlike form factor and the pair including the spectator is expected to hadronize with a hadronic form factor.

It is also of interest to examine corresponding D decays with other charges

$$D^o(c\bar{u}) \rightarrow (su\bar{d})\bar{u} \rightarrow (u\bar{u} \rightarrow M^o)_S \cdot (s\bar{d} \rightarrow \bar{K}^o)_W \rightarrow \bar{K}^oM^o \rightarrow \bar{K}^o\pi^o \rightarrow K_S\pi^o \tag{2.4}$$

$$D^o(c\bar{u}) \rightarrow (du\bar{s})\bar{u} \rightarrow (u\bar{u} \rightarrow M^o)_S \cdot (d\bar{s} \rightarrow K^o)_W \rightarrow K^oM^o \rightarrow K^o\pi^o \rightarrow K_S\pi^o \tag{2.5}$$

$$D^+(c\bar{d}) \rightarrow (su\bar{d})\bar{d} \rightarrow (s\bar{d} \rightarrow \bar{K}^o)_S \cdot (u\bar{d} \rightarrow M^+)_W \rightarrow \bar{K}^oM^+ \rightarrow \bar{K}^o\pi+ \rightarrow K_S\pi^+ \tag{2.6}$$

$$D^+(c\bar{d}) \rightarrow (du\bar{s})\bar{d} \rightarrow (d\bar{s} \rightarrow K^o)_S \cdot (u\bar{d} \rightarrow M^+)_W \rightarrow K^oM^+ \rightarrow K^o\pi^+ \rightarrow K_S\pi^+ \tag{2.7}$$

Where we note that the cabibbo-favored and doubly-suppressed amplitudes leading to final states with neutral kaons can interfere when the kaons are detected as K_S. This is of particular interest if there is any CP-violating new physics contribution.

The entire cascade of transitions (2.2) goes into (2.3) under the SU(3) $s \leftrightarrow d$ transformation, and all the purely hadronic transitions also under charge conjugation. Therefore the only strong interaction mechanisms which can break SU(3) without breaking charge conjugation must occur at the quark level and involve the differences between strange and nonstrange weak and strong form factors.

For the case where the two quark-antiquark pairs hadronize directly into the $K^+\pi^-$ and $K^-\pi^+$ final states the only SU(3) breaking effect beyond the CKM matrix elements is the weak form factor which intoduces a factor of f_π into the transition (2.2) and a factor of f_K into (2.3). This can change the relative magnitudes of the two amplitudes but does not easily introduce a phase difference. The strong form factors involve overlap integrals between different ground state s-waves and cannot easily introduce a phase.

We are then led to look for transitions where the two quark-antiquark pairs hadronize first into another intermediate state and then scatter by C-invariant strong interactions into the $K^+\pi^-$ and $K^-\pi^+$ final states. Leading candidates are the Cabibbo allowed decay modes $K^-a_1(1260)^+$ and $K^*(892)^-\rho^+$ observed experimentally with higher branching ratios than $K^-\pi^+$.

$$BR[D^o \rightarrow K^-a_1(1260)^+] = 7.3 \pm 1.1\%; \quad BR[D^o \rightarrow K^*(892)^-\rho^+] = 6.1 \pm 2.4\% \tag{2.8}$$

$$BR[D^o \rightarrow \bar{K}^o a_1(1260)^o] < 1.9\%; \quad BR(D^o \rightarrow K^-\pi^+) = 3.83 \pm 0.09\%. \tag{2.9}$$

The correspondinng doubly-Cabibbo-suppressed decay modes are therefore predicted by SU(3) to have higher branching ratios than the observed DCSD $D^o \rightarrow K^+\pi^-$. Furthermore, since they are both positive parity states, like $K^-\pi^+$, all three states are coupled together by final state rescattering. Since the a_1 and the pion have very different wave functions and are not related at all in the SU(3) limit, one might expect a difference both in magnitude and phase between the transitions

$$D^o(c\bar{u}) \rightarrow (su\bar{d})\bar{u} \rightarrow (s\bar{u} \rightarrow K^-)_S \cdot (u\bar{d} \rightarrow a_1^+)_W \rightarrow K^-a_1^+ \rightarrow K^-\pi^+ \tag{2.10}$$

$$D^o(c\bar{u}) \rightarrow (du\bar{s})\bar{u} \rightarrow (d\bar{u} \rightarrow a_1^-)_S \cdot (u\bar{s} \rightarrow K^+)_W \rightarrow a_1^-K^+ \rightarrow \pi^-K^+ \tag{2.11}$$

The suggestion of a large difference is reinforced by noting the large difference between the experimental branching ratios for the charged final state (2.8) and the neutral (2.9) for which the transition is described as

$$D^o(c\bar{u}) \rightarrow (su\bar{d})\bar{u} \rightarrow (u\bar{u} \rightarrow a_1^o)_S \cdot (s\bar{d} \rightarrow \bar{K}^o)_W \rightarrow \bar{K}^o a_1^o \rightarrow \bar{K}^o\pi^o \tag{2.12}$$

The data seem to indicate that the product of a weak axial form factor and a strong kaon form factor is very different from the reverse product. This is also expected in any model which uses factorization for the weak transition. The data for all D and B decays indicate that decays to final states containing the charged a_1 are consistently much stronger than decays to final states in the same isospin multiplet containing the neutral a_1. The data systematics seem to suggest a kind of "vector dominance" model in which D and B decays to quasi-two-body final states are dominated by diagrams in which a charged W boson turns into a charged pseudoscalar, vector or axial-vector meaon. However, better data are needed to clarify this issue.

We now note that the rescatterings $K^- a_1^+ \to K^- \pi^+$ and $K^- a_1^+ \to \bar{K}^o \pi^o$ can proceed by the same ρ exchange mechanism that has been used in the Regge exchange models [10–14] for $K - \pi$ final state rescattering. Since the strong $\rho \pi a_1$ coupling is comparable to $\rho \pi \pi$ it seems natural to extend these models to include the the $K^- a_1^+ \to \bar{K} \pi$ transition in addition to the $K - \pi$ elastic and charge exchange scattering.

Since the charged D decays (2.6) go to I=3/2 final states which are exotic and have no resonances, it might be a reasonable first approximation to neglect final state interactions for these decays and use the relations (2.6) for different intermediate states M^+ to obtain the ratio of the weak form factors between these different states..

It is also of interest to look for further tests of the same SU(3) symmetry in relations between branching ratios of neutral D decays into the final states which are equally strong and coupled by final state interactions. In the SU(3) limit these decays satisfy the relations.

$$\frac{BR(D^o \to K^+ \pi^-)}{BR(D^o \to K^- \pi^+)} = \frac{BR[D^o \to K^+ a_1(1260)^-]}{BR[D^o \to K^- a_1(1260)^+]} = \frac{BR[D^o \to K^*(892)^+ \rho^-]}{BR[D^o \to K^*(892)^- \rho^+]} = tan^4 \theta_c \quad (2.13)$$

These relations should be easily tested and provide useful insight on the breaking of SU(3) in final state interactions. They involve no phases and only branching ratios of decay modes all expected to be comparable to the observed DCSD $D^o \to K^+ \pi^-$.

However, if the SU(3) breaking is really due to the difference between products of weak axial and strong kaon form factors and vice versa, the relations (2.13) can be expected to be strongly broken and replaced by the inequality

$$\frac{BR[D^o \to K^- a_1(1260)^+]}{BR(D^o \to K^- \pi^+)} \gg \frac{BR[D^o \to K^+ a_1(1260)^-]}{BR(D^o \to K^+ \pi^-)} \quad (2.14)$$

B. Relations between D^+ and D_s decays

We now note an interesting combination of SU(3) relations [7] between Cabibbo-favored D^+ decays and doubly-Cabibbo-forbidden D_s decays and vice versa. All the obvious SU(3) breaking effects seem to cancel in this relation and the result is an unambiguous number which is either right or wrong.

Consider the ratio of branching ratios

$$\frac{BR(D_s \to K^+ K^+ \pi^-)}{BR(D_s \to K^+ K^- \pi^+)} \approx O(tan^4 \theta_c) \quad (2.15)$$

and also the ratio

$$\frac{BR(D^+ \to K^+ \pi^+ \pi^-)}{BR(D^+ \to K^- \pi^+ \pi^+)} = \frac{6.8 \pm 1.5 \times 10^{-4}}{9.0 \pm 0.6\%} \approx O(tan^4 \theta_c) \quad (2.16)$$

where we have inserted the experimental data for the D^+ decays [1].

Both of these are ratios of a doubly Cabibbo forbidden decay to an allowed decay and should be of order $tan^4 \theta_c$. The SU(3) transformation (2.1) takes the two ratios (2.15) and (2.16) into the reciprocals of one another. If strong interaction final state interactions conserve SU(3) the only SU(3) breaking occurs in the CKM matrix elements and the product of these two ratios should be EXACTLY $\tan^8 \theta_c$.

$$\frac{BR(D_s \to K^+K^+\pi^-)}{BR(D_s \to K^+K^-\pi^+)} \cdot \frac{BR(D^+ \to K^+\pi^+\pi^-)}{BR(D^+ \to K^-\pi^+\pi^+)} = tan^8\theta_c \tag{2.17}$$

This includes all SU(3) symmetric final state interactions. Thus if one of these ratios is enhanced above $tan^4\theta_c$ as seems to be the case, the other should be suppressed by the same factor, which is already interesting. This relation is seen to have the desirable feature that that most of the obvious SU(3)-symmetry-breaking factors in the individual SU(3) relations between the nummerator of one ratio and the denominator of the other seem to cancel out in this product; e.g. phase space.

This result can also be obtained from eq. (3) of ref. [7] and assuming that the neutral $K\pi$ combinations all come from K^*'s. We see here that the K^* assumption is unnecesary.

Present data [1] show $BR(D^+ \to K^+\pi^-\pi^+)/BR(D^+ \to K^-\pi^+\pi^+)$ is about 0.65% or about $3\times$ $tan^4\theta_c$. This enhancement of the doubly-Cabbibo-forbidden transition for the D^+ decay by a factor of 3 over the CKM matrix factor is normally explained away by final state interactions. But if these final state interactions obey SU(3), the relation (2.17) requires the doubly-Cabbibo-forbidden transition to be suppressed by a factor of 3 for the D_s decay.

$BR(D_s \to K^+K^+\pi^-)/BR(D_s+ \to K^+K^-\pi^+)$ should be about $(1/3) \times tan^4\theta_c$ or about 0.07%. The effects of the final-state interactions would differ by about an order of magnitude between D^+ and D_s decays.

If on the other hand the D_s decays behave similarly to the D^+ decays, the large violation of SU(3) will need some explanation. One possibility is always that there may be new physics enhancing the doubly suppressed decays. These might produce a CP violation which could show up by looking for a charge asymmetry in the products of above the two ratios; i.e between the values for D^+ and D_s decays and for D^- and $\bar{D}_s$ decays.

Furthermore, any really large SU(3)-breaking final state interactions that we don't understand must cast serious doubts on many all analyses and predictions for heavy-flavor decays which use SU(3) and neglect the possibility of such final state interactions.

One interesting possibilty might be the enhancement of the "non-exotic" final states by the presence of hadronic meson resonances at the D and D_s masses. These could explain the enhancement of the doubly-forbidden D^+ decay and preserve the SU(3) relation by similarly enhancing the allowed D_s decay. The doubly-forbidden D_s decay and the allowed D^+ decay lead to states having exotic quantum numbers which have no resonances.

An obvious caveat to this analysis is the almost trivial SU(3) breaking arising from resonances in the final states. But with sufficient data and Dalitz plots it should be possible to take these resonances into account or look at domains in the Dalitz plots where they do not appear in order to pinpoint possible sources of SU(3) breaking.

In any case the SU(3) relation (2.17) and its possible violations raise interesting questions which deserve further theoretical and experimental investigation.

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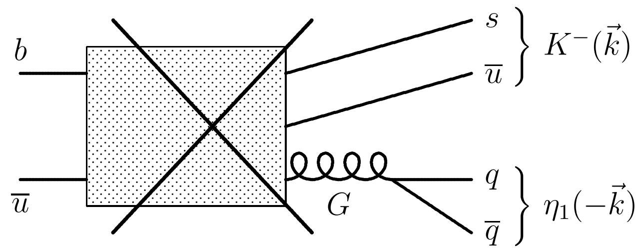

FIG. 1.
Forbidden “gluonic hairpin” diagram. G denotes any number of gluons.

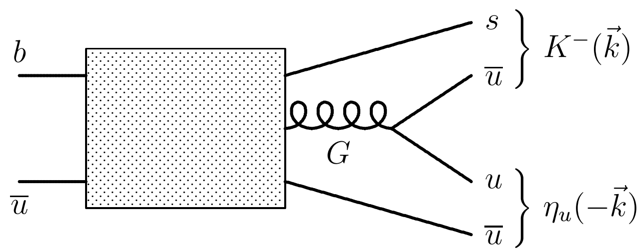

FIG. 2.
Strong $u\bar{u}$ pair creation. G denotes any number of gluons.

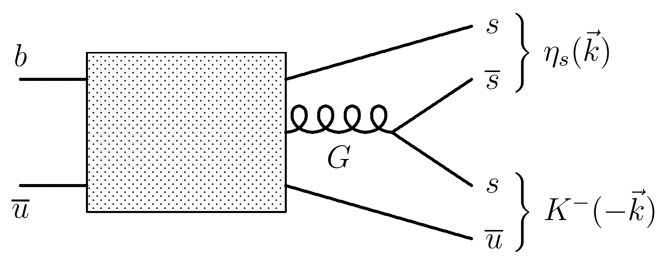

FIG. 3.
Strong $s\bar{s}$ pair creation. G denotes any number of gluons.

$$A[\eta_s(\vec{k})K^-(-\vec{k})] = A[\eta_u(-\vec{k})K^-(\vec{k})] = P \cdot A[\eta_u(\vec{k})K^-(-\vec{k})]$$

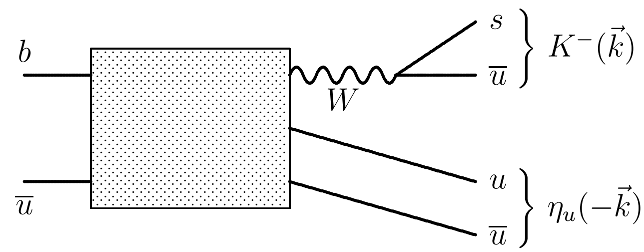

FIG. 4.
Color favored tree diagram.

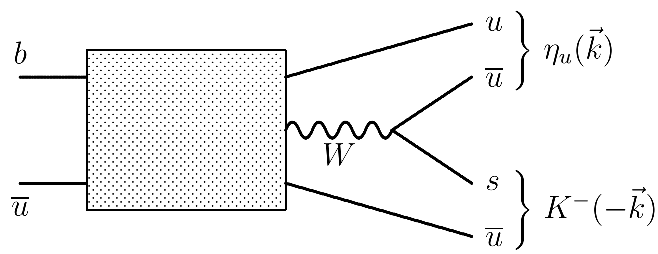

FIG. 5.
Color suppressed tree diagram.

$$\frac{A[\eta'(\vec{k})K^-(-\vec{k})]}{A[\eta(\vec{k})K^-(-\vec{k})]} = \frac{\langle \eta_u \,|\eta' \rangle}{\langle \eta_u \,|\eta \rangle}$$

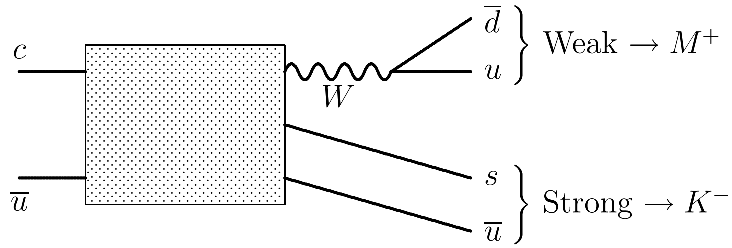

FIG. 6.
Color favored Cabibbo favored diagram.

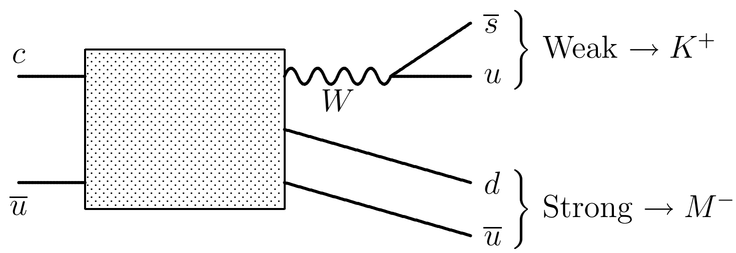

FIG. 7.
Color favored Cabibbo Doubly-Suppressed diagram.